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ABSTRACT

Due to the transcritical nature, some of the test methods used in the conventional subcritical refrigeration cycle, such as the liquid refrigerant flow metering method and the water-cooled condenser metering method, are no longer appropriate for evaluating the transcritical carbon dioxide (CO_2) compressor performances.
This paper introduces a performance test facility taken into account both the transcritical and the subcritical operating conditions for CO_2 compressor, including design requirements and parameter control, the main technical challenges and solutions in the laboratory testing facility development. The compressor refrigerating capacity major test results with this setup are compared to the auxiliary test and found less than 4% discrepancies. In addition, this test facility has high test repeatability. Due to these advantages, it is being used to provide experimental data and technical support for the new China National Standard (GB) "Positive Displacement CO_2 Refrigerant Compressor Unit".

1. INTRODUCTION

Environmental concerns and regulations in the last two decades have generated the need for extensive research to identify viable and "environmentally friendly" refrigerant alternatives on so-called natural refrigerants (e.g., carbon dioxide, ammonia, hydrocarbons, air, water, etc). Carbon dioxide (CO_2) as a non-toxic, non-combustible, easy availability, low price and no need of recycling natural refrigerant has attracted more and more interests in refrigeration applications as possible replacement of fluorocarbon-based refrigerants used at present for vapor compression cycle technology (Boewe *et al*., 2001; Hubacher *et al*., 2002; Huang *et al*., 2007; Padalkar *et al*., 2010).In particular, the transcritical CO_2 cycle has recently been investigated for certain applications, such as automobile air conditioners, heat pump water heaters, and environmental control units.

Compared to conventional refrigerants, the most remarkable property of CO_2 is the low critical temperature of 31.1℃. Vapour compression systems with CO_2 operating at normal ambient temperatures thus work close to and even above the critical pressure of 7.38 MPa. This leads to two distinct features of CO_2 systems: heat is rejected at supercritical pressure in many situations and the pressure level in the system will be quite high (Nekas, 2002; Dreiman, 2004). Scholars have done a lot of work on CO_2 refrigeration technology and its applied research in the field of refrigeration. A review can be found in Sarkar (2010).

Due to the quite important significance to research and development of CO_2 compressors, it is conducted specifically that research focused on the CO_2 compressor performance test facility for measuring the compressor capacity and coefficient of performance. However, the distinct differences with freon refrigerants in property lead to the differences in test parameters' control. It is rarely seen that experiment rigs specifically for CO_2 compressor performance test in China at present. And the smooth research and development work on the CO_2 compressor has been restricted. On the basis of understanding about the high pressure specificity of CO_2 and a large number of experiences in construction of refrigerant compressor test devices, the State Key Laboratory of Compressor

Technology of China developed a set of CO_2 compressor comprehensive performance test facility for both the transcritical and the subcritical cycle operating conditions.

2. CO_2 COMPRESSOR PERFORMANCE TEST FACILITY

The essence of construction of refrigerant compressor performance test facility is to construct a refrigeration cycle, make operating condition parameters such as the suction state point (pressure and temperature), the discharge state point (pressure) of compressor and ambient temperature be controllable. In addition to these purposes, this CO_2 compressor performance test facility also takes into account the versatility, the stability and the rapidity of parameters' adjustment altogether. The schematic is shown in Fig. 1.

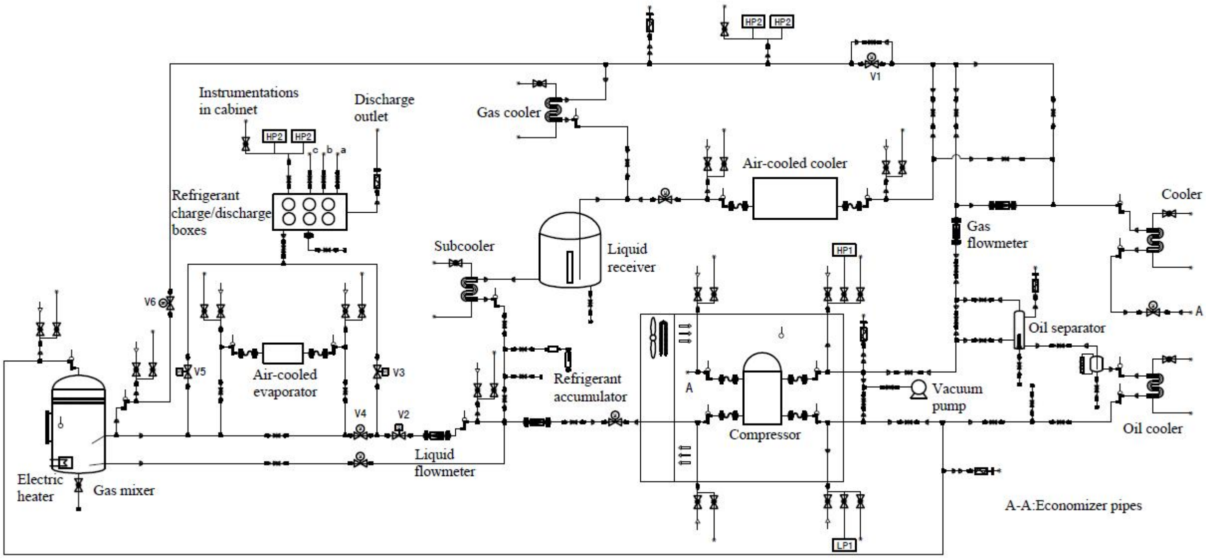

Figure 1: Schematic view of the test facility

The test facility set up in accordance with an improved refrigerant vapour cooling method was built up for carrying out various experiments on the CO_2 compressors. The design cooling capacity ranges from 14kW to 70kW. It is consisted of an environmental chamber of compressor, gas flowmeter, expansion valve, gas cooler, reservoir, subcooler, liquid flowmeter, gas mixer, oil separator, refrigerant accumulator, some kinds of electric control valves, and so on. Eleven pressure transducers and nineteen temperature sensors were installed in the test facility. Basically, one pressure and temperature sensor was placed before and after each key component.

The improved refrigerant vapour cooling method behind this facility is also named hot-gas bypass method, which is to anchor the intermediate pressure below the critical pressure in the two-phase region. The suction and discharge pressures are controlled using appropriate regulating valves in the discharge line and bypass line. In the primary loop of the test system, gas cooler and subcooler are cooled by cooling water system which is responsible for providing the cold source. A liquid throttle valve is installed at the liquid pipeline before the gas mixer and adjusted by PID instruments. The high temperature CO_2 would be condensed in the gas cooler and further cooled in the subcooler. Then the subcooled liquid exits the heat exchanger and is throttled through the primary expansion valve to the suction pressure level. In the bypass loop of the test system, gas flowmeter and discharge pressure throttle valve are installed at the discharge pipeline. The fluid is throttled directly to the suction pressure level by the bypass expansion valve.

The compressor discharges supercritical, high pressure CO_2, which is throttled to the intermediate pressure equal to the condensation pressure by the discharge pressure valve. The flow is split after passing through the main flow meter. Most of the flow goes through the bypass loop while the remaining one enters the primary loop. The two fluid streams are then combined in the gas mixer, where the outlet status of the CO_2 approximates the compressor suction status (Hwang and Radermacher, 1998; Christen *et al*., 2006).

There is a refrigerant charge and recovery system paralleling to the primary loop. And the test compressor is connected with the economizer pipes, in which an internal cooling device is included. The oil circulation is composed of oil cooler (cooled by the external cooling water), oil accumulator and oil separator. Because of two additional dedicated test boards, this facility also can be used for testing the performance of the gas cooler and the evaporator for CO_2 refrigeration system.

3. DESIGN PRINCIPLES

3.1 Design requirements

Design and selection of system pipes, containers, valves and other fittings are based on the thermal performance calculation results of various components at the design conditions (the selection of valves should be combined with the valve characteristic curves). Main design requirements and details are described as follow.

3.1.1 System pipelines: For special pressure requirements of the CO_2 system, this test facility pipelines are all made of stainless steel pipes. The pipe connection types, including argon arc welding, ferrule fitting and flange ways, are effectively to ensure good sealing of the system and make the pipelines easily removable and quickly fixed.

a) The maximum pressure of the system is 16Mpa; The maximum temperature of the system is 140℃.
b) Suppressing the pressure up to 24Mpa and maintaining for 24 hours without leakage.
c) The entire pipelines are covered with insulation layers (thickness range from 50mm to 100mm).
d) The pipelines designed should in accordance with two China mandatory regulations: the Special Equipment Safety Supervision Regulations and the Pressure Pipeline Safety Management and Monitoring Requirements.

The materials used in the system framework comprise channel irons and profiled steels together. And the diameters of the stainless steels used in the facility involved several types: φ6*3mm, φ10*3mm, φ16*3mm, φ20*3mm and φ22*3mm.

3.1.2 Heat exchangers: Three heat exchangers are used as main parts of the test facility, all of them have good pressure capabilities. The specifications are listed in Table 1.

Table 1: Overview of heat exchanger requirements

	Gas cooler		Subcooler		Cooler (Economizer)	
	Water side	CO_2 side	Water side	CO_2 side	Water side	CO_2 side
Maximum flow (m^3/h)	4.3 (△T:5℃)	305.9 (92.1℃,7.38MPa)	1.4 (△T:5℃)	305.9 (31.1℃, 7.38MPa)	0.6 (△T:5℃)	61.2 (92.1℃,8.5MPa)
Inlet/outlet temperature(℃)	15→20	85.5→31.1	5→10	31.1→9.1	45→50	92.1→73.8
Operating Range (℃)	$T_{ambient}$～70	$T_{ambient}$～100	$T_{ambient}$～70	$T_{ambient}$～90	$T_{ambient}$～70	$T_{ambient}$～180
Maximum allowable pressure loss (kPa)	100					
Maximum permissible pressure (MPa)	0.5	9	0.5	9	0.5	15
Heat exchanger type	plate heat exchanger				double-pipe heat exchanger	
Heat transfer capacity(kW)	25		8		3.5	

Note: △T—temperature difference.

3.2 Parameter control

Basic control parameters of the test facility involve suction pressure, suction temperature, discharge pressure and ambient temperature around compressor. The following Table 2 presents these parameters and their control means, control scopes and control accuracies.

And there are six control valves used in the main circuits of the test facility (see Fig.2). The functions and states of the vavles differ according to the system operating conditions.

V1: A discharge pressure manual regulation throttle is in the fully open state at subcritical test conditions, and is used for adjusting the discharge pressure at transcritical test conditions.

V2: An electric valve operated by the touch screen (ON/OFF) is in the open state during the test and after the test.

Table 2: Overview of control parameters

Parameter	Control Means	Control Scope	Control Accuracy
Suction pressure	Adjust refrigerant vapour flow by electric control valve at the bypass line	0.0～8.0MPa	±1.0%
Suction temperature	Adjust refrigerant liquid flow by throttling valve at the condensate line	-50℃～80℃	±0.1℃
Discharge pressure	Adjust cooling water flow by inverter control pump	0.0～17.0MPa	±1.0%
Ambient temperature around compressor	Adjust heating power by SCR	-200℃～200℃	±0.5℃

V3: An electric valve operated by the touch screen (ON/OFF) turns off during the test and is in the open state after the test, which is used for recovering the excessive refrigerant of the system.
V4: A liquid throttle adjusted by the PID is used for controlling refrigerant liquid-flow into the gas mixer.
V5: An electric valve operated by the touch screen (ON/OFF) turns off during the test and is in the open state after the test (the charging amount of refrigerant in the refrigerant charge and recovery boxes is an important factor to affect the compressor discharge pressure).
V6: A hot gas bypass valve adjusted by the PID is used for controlling refrigerant gas-flow into the gas mixer.

4. TECHNICAL CHALLENGES AND SOLUTIONS

4.1 Technical challenges

According to the traditional test system design ideas, various components in the refrigeration system such as oil separator, condenser, liquid reservoir, ball valves and filters all should adopt high-pressure products (All these components should have reliable performance under high pressure condition). Some of the pressure vessels are equipped with safety valves which can automatically open for releasing the refrigerant gas in the container while the pressures inside are higher than the set ones, then the pressure quickly reduces. However, the refrigerant fluid (CO_2) before the safety valve is supercritical or in form of vapor-liquid two-phase state, and the refrigeration system operating pressure sometimes could even up to 15MPa or even higher at the transcritical cycle conditions. The refrigerant discharge pressure is higher than the discharge back-pressure (atmospheric pressure), ice block phenomenon may occur in the emission process, which usually blocks the safety valves due to very low temperature in a very short time. For there is no place for releasing of the high pressure refrigerant, it is possible to make the container overpressure explode. So, problems of high-pressure safety should be effectively resolved in the research and development of the CO_2 compressor performance test facility.

4.2 Solutions

First, the test facility sets an electric cut-off valve and a set of regulator decompression components composed of automatic decompression valves between the compressor discharge port and discharge gas flow meter. The electric cut-off valve opens when compressor operating discharge pressure is no more than 4.2MPa (or the upper limit allowable pressure of the parts), then refrigerant directly get into the cycle system. On the contrary, the automatic decompression valves turns on immediately to send down discharge pressure to safety level after the electric cut-off valve turns off.

Second, the test facility also sets safety valves and security components composed of precision temperature switches and electric ball valves on oil separator, gas cooler, liquid receiver and subcooler. The temperature switches opening while the system pressure higher over the normal level. The refrigerant escapes from the electric valve rapidly, and may lead the CO_2 temperature slide down to a large extent until the temperature reduces to the default value of the precision temperature switches. Then the overpressure will rapidly discharge to ensure safety in that the ball valve flow coefficient is much larger than that of the safety valve, and then a large number of overpressure CO_2 could be branched off.

As the third technical solution way, refrigerant charge and recovery system is annexed in the liquid refrigerant pipe. In case the test facility is temporarily disabled for the high pressure, refrigerant could be control to get into the recovery system for reducing the pressure of other containers or components and protecting the whole facility (Tian *et al.*, 2009).

5. TEST RESULTS

One reciprocating single stage CO_2 compressor was used for testing with the rating frequency of 50 Hz). The test facility running on the basis of the improved refrigerant vapour cooling metering method and the refrigerant vapour flowmeter metering method at the same time.

5.1 Deviations between primary test and auxiliary test

After debugging and operating, control parameter accuracy of the compressor test facility were confirmed at the following conditions.

5.1.1 Subcritical cycle: With the different evaporation temperature of -5℃,-10℃ and -20℃, the superheat of 10℃, the condensation temperature of 25℃ and the subcooling degree of 5℃. The performance tolerances (deviations between the test data and the manufacture's stated performance) of the refrigerant compressor tested in the facility with three subcritical conditions are shown in Fig.2. Based on the measured data get from multiple test channels, the respective calculated average values of the test balance deviations between the two methods for each cycle are 2.599%, 1.392% and 0.949%.

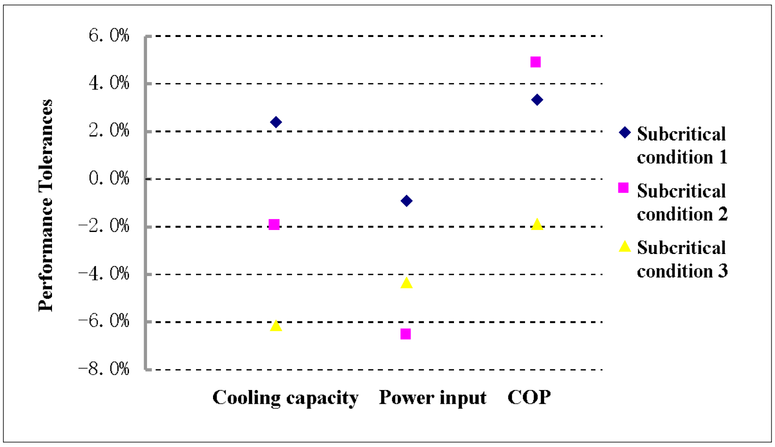

Figure 2: Performance tolerances tested in the facility for three different subcritical cycles

5.1.2 Transcritical cycle: Four typical transcritical cycle tests were operated in the facility. The calculated average values of the test balance deviations between the primary test and auxiliary test are presented in Table 3.

Table 3: Overview of test results for four different transcritical cycles

Condition	Suction Temperature(℃)	Evaporation Temperature(℃)	Discharge Pressure(MPa)	Liquid Flowmeter Inlet Temperature(℃)	Primary/Auxiliary Test Deviation Values
Cycle type1	20	10	8.5	18.1	1.196%
Cycle type2	5	-5	9	12.7	3.889%
Cycle type3	0	-10	8	11.7	1.446%
Cycle type4	20	10	10	18.4	2.322%

5.2 Repeatability

Repeatability of the test facility means the deviation of test results under the same experimental conditions but different times. It is also an important evaluation indicator to the test facility, which can take the control precision of the parameters into account. The repeatability of test facility could be checked periodically on one compressor at a constant test condition. The conditions for this test were a suction pressure of 3045 kPa, suction temperature of 5℃, discharge pressure of 7377 kPa and evaporation temperature of -5℃. By comparing the single stage compressor performances for the various tests, conclusions about the test facility repeatability can be made. Figure 3 presents the results of six tests. All the test intervals were more than 24 hours. It can be seen that data of the power input and the refrigeration capacity are very repeatable, and the measured repeatability deviations of these six tests all less than 2%.

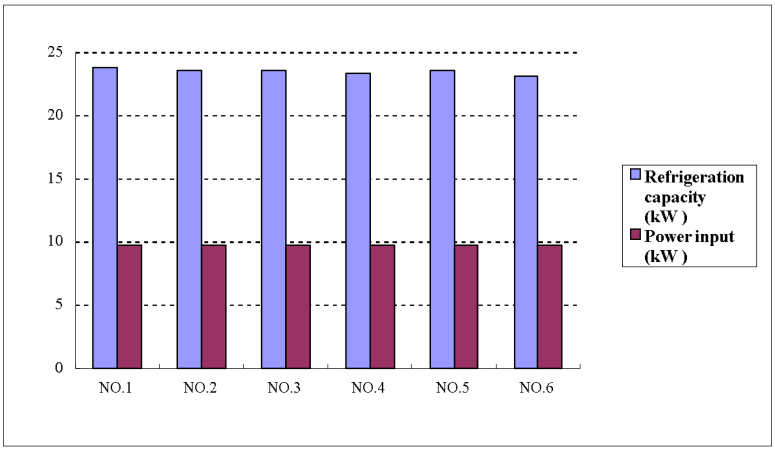

Figure 3: Repeatability testing for the power input and the refrigeration capacity for six different tests

All these results verified the reliability of this test facility running at both the transcritical and the subcritical cycle conditions.

6. TEST METHOD IN CHINA NATIONAL STANDARD

The new China Standard (GB)"Positive Displacement CO_2 Refrigerant Compressor Unit" determines the nominal operating conditions and performance test methods. And most of demonstration tests of the nominal operating conditions are based on the mentioned test facility.

So far as the performance test methods are concerned, the liquid refrigerant flow metering method and the water-cooled condenser metering method used in the conventional subcritical refrigeration cycle are no longer appropriate for evaluating the transcritical CO_2 compressor performances due to the transcritical nature. Based on experimental data get from the test facility, the feasibility of verified refrigerant vapour cooling method using for transcritical refrigeartion cycle has also been confirmed. The new GB covers the specific operational procedure of this improved method. Fig.4 shows the flow chart. Different from the previously common refrigerant vapour cooling method, a key throttle valve is added behind the compressor discharge port in the test system.

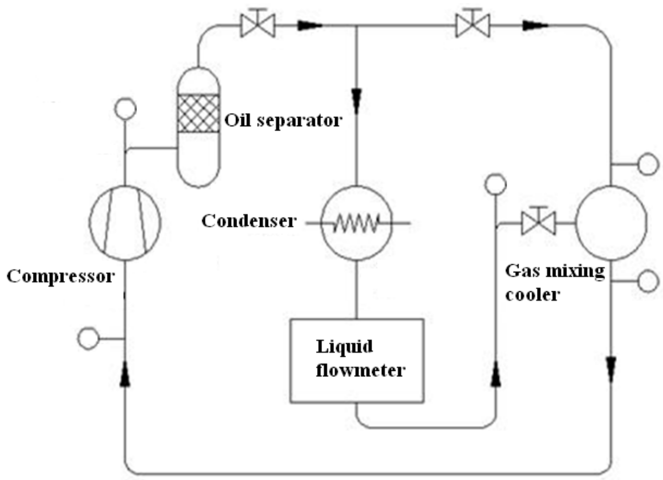

Figure 4: Improved refrigerant vapour cooling method flow chart in the GB standard

7. CONCLUSIONS

This paper introduced the characteristics of the transcritical carbon dioxide refrigeration cycle and a positive displacement CO_2 compressor performance test facility which taken into account both transcritical and subcritical cycle with design cooling capacity ranged from 14kW to 70kW. The design requirements of main components and parameter control were also given. Technical challenges and three corresponding solutions were described during the construction process of the facility.

A reciprocating CO_2 refrigerant compressor was tested using this compressor performance facility at different subcritical/transcritical conditions. The compressor refrigerating capacity major test results with the setup were compared to the auxiliary test and found less than 4% discrepancies. High repeatability of measuring data tested in the facility was verified (repeatability deviations were found within 2% for six times). And the actual operation control parameters of the CO_2 compressor always fluctuated within the scope of design. Based on these test data, conclusion about the facility reliability could be made.

Due to these, the test facility is being used to provide experimental data and technical support for the new China National Standard, in which the improved refrigerant vapour cooling method was included.

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